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C-5A AUSTERE AIRFIELD OPERATIONAL UTILITY EVALUATION: PHASE II-Operation on Unpaved Soil Surfaces Following Rainfall

W. O. Breuhaus, *Project Leader*

DTIC ELECTE DEC 16 1981 S D B

October 1981

Prepared for
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REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER / 2. GOVT ACCESSION NO. AD-A108 597	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) C-5A Austere Airfield Operational Utility Evaluation, Phase II — Operation on Unpaved Soil Surfaces Following Rainfall	5. TYPE OF REPORT & PERIOD COVERED FINAL
	6. PERFORMING ORG. REPORT NUMBER IDA Paper P-1621
7. AUTHOR(s) W. O. Breuhaus	8. CONTRACT OR GRANT NUMBER(s) MDA903 79-C-0018
9. PERFORMING ORGANIZATION NAME AND ADDRESS Institute for Defense Analyses 400 Army-Navy Drive Arlington, Virginia 22202	10. PROGRAM ELEMENT PROJECT TASK AREA & WORK UNIT NUMBERS T-1-099
11. CONTROLLING OFFICE NAME AND ADDRESS OUSDRE Room 3E130, The Pentagon Washington, D. C. 20301	12. REPORT DATE October 1981
	13. NUMBER OF PAGES 50
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) DoD-IDA Management Office 400 Army-Navy Drive Arlington, Virginia 22202	15. SECURITY CLASS (of this report) UNCLASSIFIED
	15a. DECLASSIFICATION DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

None

18. SUPPLEMENTARY NOTES

None

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

C-5, C-5A, C-5A OUE, C-5A Operational Utility Evaluation, Austere Airfields, Unprepared Airfields, Rainfall Effects on Surface, CBR, California Bearing Ratio

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

During the summer of 1980 and the winter of 1980-1981, an Operational Utility Evaluation (OUE) was conducted to determine operating characteristics of the C-5A airplane when taxiing or being towed and off-loaded on unpaved soil surfaces and on snow-covered surfaces. Subsequent to the successful completion of those tests, questions arose concerning the effects of rainfall that wets otherwise adequate bare soil areas to a significant depth. Tests with simulated rainfall of various amounts applied by agricultural sprinkler systems were conducted at March AFB, California, during July 1981. The airplane performed well, though it

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20. ABSTRACT (continued)

approached its performance limits in the most severe test conditions. Difficulties were encountered in arriving at a sprinkler system configuration reasonably approximating naturally occurring rainfall, and in arriving at a single simple descriptor to properly characterize the strength of soil in such a complex situation.

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C-5A AUSTERE AIRFIELD OPERATIONAL UTILITY EVALUATION: PHASE II–OPERATIONAL EVALUATION ON UNPAVED SOIL SURFACES FOLLOWING RAINFALL

A. INTRODUCTION

During the summer of 1980 and the winter of 1980-1981 an Operational Utility Evaluation (OUE) was conducted to determine operating characteristics of the C-5A airplane when taxiing on unpaved soil surfaces and on snow-covered surfaces. Additional tests determined the ability to tow the airplane and to offload cargo from it in these conditions.

Subsequent to the completion of these tests, questions were raised concerning the effects of rainfall that wets otherwise adequate bare soil areas to a significant depth. An additional test phase was designed and conducted to investigate this condition.

The tests were conducted at March AFB, California, during July 1981, in accordance with a test plan prepared by the Air Force Test and Evaluation Center. The test plan specified a clay surface but, in the summer of 1981, widespread heavy rainfall rendered the surfaces of all bases with clay soil too wet and soft to be used. March AFB was chosen, and controlled amounts of rainfall were simulated by use of agricultural sprinkler systems. The soil at March AFB is a silty sand and has characteristics that differ from those of clay. However, the silty sand is similar to the soils of a number of airfields in Europe.

The airplane again performed well, though it approached its performance limits in the most severe test conditions. Considerable difficulty was encountered in arriving at a sprinkler system configuration that reasonably approximated naturally occurring rainfall. Also, the difficulty of arriving at a single simple descriptor to properly characterize the strength of soil in such a complex situation was apparent.

The tests were observed by an IDA representative from July 6 through 10, and the information from the remainder of the tests (through July 19) was collected following the completion of those tests. The results in this report supplement those in Reference 1, which should be consulted for a complete description of the Operational Utility Evaluation.

B. BACKGROUND

An Operational Utility Evaluation (OUE) was conducted during the summer of 1980 to determine the capability of the C-5A airplane in ground operations on unpaved soil surfaces. This OUE was confined to taxiing operations at speeds of 10 knots (or less), towing operations, and the offloading of cargo on the unprepared soil surfaces. The results of these tests,

and more detailed discussion of the background leading to the decision to conduct the OUE, are contained in References 1 and 2. Reference 1 should be considered in conjunction with this report. Results from Reference 1 are summarized in Appendixes A and B.

The initial OUE was conducted in hot and dry summer conditions on relatively hard ground. It was directed that the tests be conducted on soil with a hardness no less than that described by a California Bearing Ratio (CBR) of 9.[1] Some tests were also conducted on aluminum matting laid over softer soil. The tests were conducted at Shaw AFB, Altus AFB, and Eglin AFB, and the airplane was operated without difficulty (though towing operations could not be conducted consistently on the sandy soil at Eglin AFB, because of loss of traction of the towing vehicles[2]).

Following successful completion of the above tests, the decision was made to extend the OUE to include ground operation in approximately 12 inches of snow over frozen ground. This extended evaluation was conducted at Griffiss AFB, New York, in January 1981. Again the taxi and offload operations were completed successfully,[3] though towing of the airplane was not possible when the tow vehicles were located on snow- or ice-covered surfaces. The results from the evaluation conducted in snow are contained in References 1 and 2.

A question was raised as to the effect of rainfall on operations conducted on ground with a hardness rated CBR 9 or greater. The question addressed the effect of the rain on the surface, and the accompanying rutting, possible skidding, or reduced controllability of the airplane on the slippery surface, and the adhesion of mud to the airplane. This was judged to be a surface effect, and it was not proposed that the soil strength at appreciable depths below the surface be significantly reduced. Note, however, that no precise definition of "significant depth" is given. The overall objective of the program (stated in Reference 3) is "to evaluate the effects of rainfall on C-5A ground operations on unprepared airfield surfaces with strengths of CBR 9 and above."

This evaluation was conducted at March AFB in July 1981. Varying amounts of rainfall on the surface were simulated by the use of irrigation sprinkler systems.

C. ORGANIZATION OF TESTS AND TEST SITE SELECTION

The test program was prepared by the Air Force Test and Evaluation Center (AFTEC) and is contained in Reference 3. The tests were run under the direction of AFTEC, with the Military Airlift Command (MAC) supplying the C-5A airplane, Ground Support Equipment, and personnel for maintenance and operation of the airplane and for loading and offloading the airplane. The vehicles used for the offloaded cargo were supplied by the Army. The measurement of soil characteristics and soil engineering were supplied by personnel of the Waterways Experiment Station (WES) of the Army Corps of Engineers and of the Air Force Engineering Services Center (AFESC). The organization and operation of the test team were similar to those of the earlier C-5A OUE tests reported in References 1 and 2.

1. For discussion of CBR, see Appendix C, pp. C-1 to C-4.

2. See Appendix A, p. A-1, and Reference 1, p. 46.

3. See Appendix B.

The initial planning for the test site indicated that a clay-type soil with strength corresponding to a CBR of 9-14 would be desirable.[4] Clay was selected because of its poor drainage characteristics, slippery surface when water is added to a previously dry clay surface, and generally sticky mud produced when water is added to clay. However, in the early summer of 1981, heavy and prolonged rain had reduced the strength in areas where clay soil was available (e.g., Kelly AFB, Texas, Whiteman AFB, Missouri, Wright-Patterson AFB, Ohio) to values less than CBR 9. Altus AFB, Oklahoma, was considered next. The final classification of the soil at Altus, made during the earlier C-5A OUE tests conducted there in the summer of 1980, showed that this soil was a sandy clay with a subgrade of silty clay.[5] Testing at Altus was deemed to be advantageous because of familiarity with that base gained during the earlier OUE tests. However, unusually heavy rainfall at Altus weakened the soil and forced abandonment of plans to conduct tests there. March AFB was finally selected as the test site. The normal annual rainfall at March is approximately 11 inches, and, in the year ending June 1981, approximately 7 inches had fallen. Therefore, unlike the other bases that had been considered, the soil at March was very hard and dry before water was applied, and its strength was considerably greater than that characterized by CBR 9.[6]

The soil at March AFB is classified as silty sand. While this soil does not have the same characteristics as moistened clay, it is nevertheless not unlike the soil type found in Central Europe, and in West Germany in particular. A soil survey conducted by AFESC and WES at nine different West German airfields showed that sandy silt (not precisely the same as silty sand) was a substantial component[7] of the soil at the majority of these airfields. However, the drying rates at March AFB exceed those in Central Europe because of the low relative humidity, high temperature (mid-day temperatures between 90° and 100° F at the time of the tests), and steady afternoon breeze.

D. TEST CONDITIONS

The test plan [Ref. 3] called for tests under three different simulated rainfall conditions. Separate test areas were laid out for each of these conditions, and taxi and cargo offload events were conducted in each of these test areas. The specified rainfall characteristics were as follows:

(1) Normal rainfall. A total of 1½ to 2 inches of rain was to be applied in 2 to 3 days in equal increments, with soil measurements and tests with the airplane to be conducted between increments.

(2) Extended rainfall. Rain was to be applied in increments of approximately ½ inch per day with soil measurements and airplane taxi tests conducted daily. This was to

4. See Reference 3, pp. 5 and 14.

5. See Reference 2, p. 46.

6. Measured soil strength at March AFB is discussed in the section on Soil Characteristics, p. 8.

7. Most of the airfields surveyed showed more than one type of soil at each field.

be continued until either a limit of airplane performance or soil failure (CBR is less than 9)[8] was reached.

(3) Maximum rainfall. Rain was to be applied continuously until approximately 2 inches had been applied to the ground in less than 24 hours.

A 300- by 600-foot area was laid out for each of the three rainfall conditions. These areas are shown in Figure 1 as they were laid out relative to runways and taxiways at March

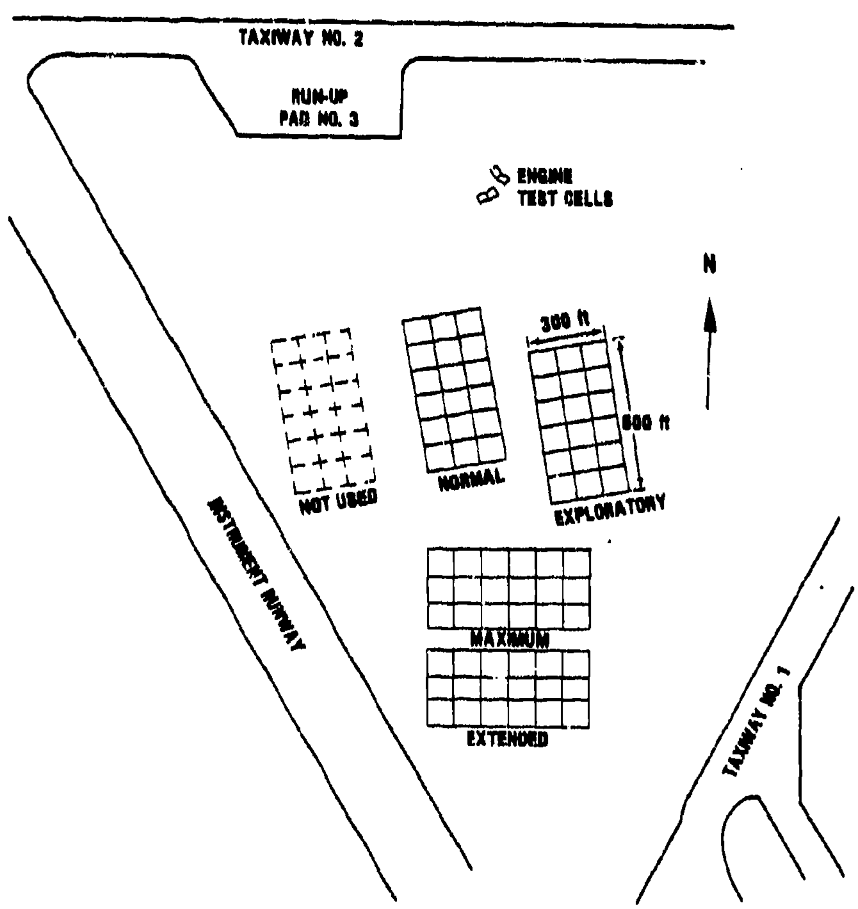

Figure 1. Test Area Locations—March AFB

8. The criterion adopted for determining if CBR is less than 9, allowing for vertical gradient of soil strength, is described in the section on Soil Characteristics, p. 8.

AFB. Each test area was divided into 100- by 100-foot grid squares, and soil hardness and precipitation were measured at these grid point locations. The three northern-most test areas shown in Figure 1 were originally intended for the three different precipitation conditions described above. However, the area originally designated for the extended tests was used for rain-making exploratory tests and initial taxi experimentation. It could not then be used for the planned extended rainfall test, and the area originally intended for the maximum test was abandoned. Two new areas, south of the original areas and shown in Figure 1, were laid out and were used for the extended and the maximum tests.

E. SIMULATION OF RAINFALL

Rainfall was simulated by use of commercial agricultural irrigation sprinkling equipment. Though satisfactory for its intended agricultural purposes, this equipment did not readily yield the uniform application of water required here, and the initial part of the test program was devoted largely to experimentation with the sprinkler system. These efforts are described below in some detail to explain the difficulties encountered in attempting to quantitatively simulate natural rainfall.

The sprinkler system consisted of sections of water line, approximately 6 inches in diameter and 40 feet long. The lines were at the center of large wheels (roughly 6 feet in diameter) that allowed moving the lines by rolling the wheels along the ground. Enough sections of line were joined together to permit covering the length of a test area (600 feet), and rotating sprinkler heads were placed at intervals along the lines. Enough parallel lines were provided to permit the sprinkler heads to cover the test area.

The original attempts to produce simulated rain utilized high capacity sprinkler heads that had a rated diameter of application of 180 feet. Four heads were used on each line, and two parallel lines were used, as shown in Figure 2. When this arrangement was tried, it produced a very non-uniform pattern of application. The distribution of water depth, as a function of radius measured from each sprinkler head, was non-uniform; this produced concentric bands of precipitation depth. This system was used in the area marked "exploratory" in Figure 1, and initial taxi tests (to be described later) were performed. The results were unsatisfactory, and the sprinkling system was revised extensively.

The size of the sprinkler heads was substantially reduced, and the number was increased from 4 to 10 per line. (These heads had a rated sprinkling diameter of 80 feet rather than the 180 feet of the original heads.) The number of parallel lines was increased from two to three (see Fig. 2), and these were placed so that only half of the width of a test area (150 feet) was covered during a sprinkling operation. It was then necessary to roll the lines to the other half of the area and repeat the sprinkling cycle.

A final fine tuning resulted in the use of four parallel lines with sprinkler heads of a lesser flow rate (see Fig. 2), which was the configuration used for final testing in the extended and maximum areas. This multiplicity of equipment and the need to make frequent movements of it resulted in much manual labor and movement of sprinkling equipment at all hours of the

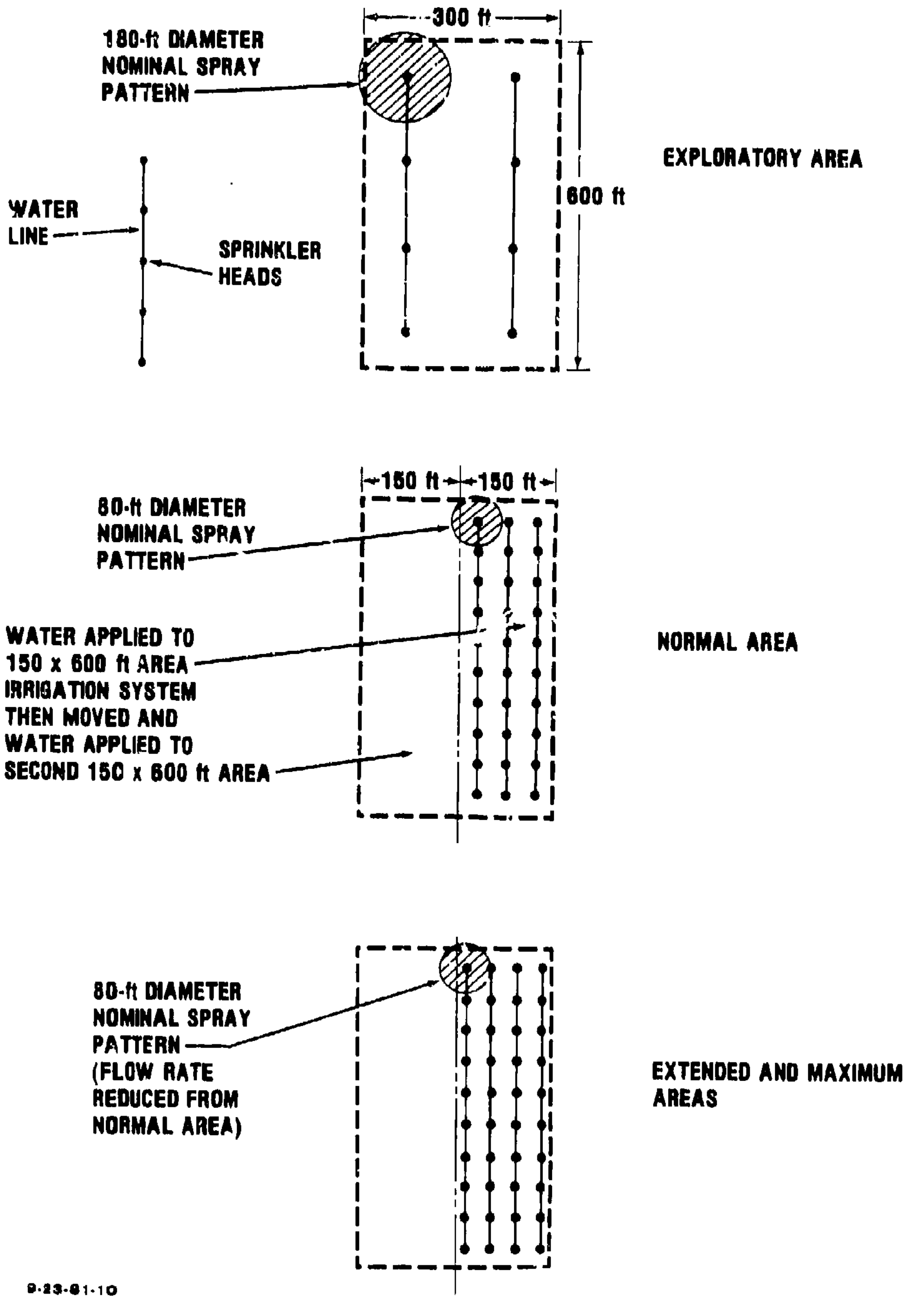

Figure 2. Sprinkling System Patterns

day and night, but other more insidious difficulties emerged before the final configuration and method of use were arrived at.

When the tests began with the three-line sprinkler system in the "normal" area, isolated small areas of greater-then-average soil disturbance were noted after the initial taxi tests.[9] These were noted after the first application of about 0.5 inch of water, but the reason for this was not known.

Following the third application of water in the normal area (for a cumulative total of about 1.75 inches), it was discovered that deep, soft areas of earth, perhaps 10 feet in diameter, existed at the locations of many of the sprinkler heads and sprinkler line joints. (The heads were located near these joints, though not every joint necessarily had a head.) The soil in these areas was soft, and the soft soil continued to a depth of 2 to 3 feet at many locations. These were discovered by probing with an Airfield Penetrometer, and values of Airfield Index (AI) obtained with the penetrometer in these areas varied from 1 to 4 (CBR values would be roughly similar to the AI values).[10] These deep soft spots, located at roughly 40-foot intervals throughout the test area, created abrupt "holes" hazardous to the airplane landing gear and could not be tolerated. They had increased in size and softness with repeated waterings.

Investigation showed that concentrated leakage occurred from sprinkler head drain valves and from the pipe joint seals when the water pipe was filled but pressure in the lines was reduced.[11] Reduced pressure existed whenever the water was initially turned on and the lines were filling and again when the water supply was turned off. Apparently the lines were returned to the same position for each sprinkling cycle with sufficient accuracy that the drainage fell in essentially the same location for each sprinkling cycle and caused deep soakage of the water there.[12]

The tests were halted and a concentrated effort expended to refine the sprinkling system. The sprinkler drain valves were plugged (an effort that sounds simple but in fact required several modifications and the expenditure of considerable time and effort), and the effectiveness of the pipe joint sealing at low pressure was improved. This resulted in the need to move the lines when they were full of water. Each 560-foot long, 6-inch diameter line contained approximately 3.5 tons of water when filled, making the movement of the lines over the softened soil physically difficult and imposing considerable stress on the pipe joints and the wheels (the spokes and rims of the latter suffered some deformation as a result of these loads). The lines were moved immediately after the water pressure was turned off so that whatever leakage occurred would not be concentrated in a localized area. Large cans were also placed under those joints where leakage appeared to be excessive, and the contents of these cans were distributed over large areas.

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9. These test results will be discussed in more detail in the section on Test Results, Tests in Normal Area, p. 15.

10. For a description of the airfield penetrometer and the Airfield Index, see Appendix C, p. C-4.

11. The drain valves opened at low pressure to permit the water in the lines to drain and thus reduce the weight of water in the system. This permitted easier movement of the lines, a desirable feature for ordinary agricultural usage. The joint seals did not seal effectively unless pressurized, which again was not a disadvantage for agricultural use.

12. Each 6-inch diameter, 40-foot length of sprinkler pipe contained nearly 60 gallons of water.

Watering usually took place at night and in the early morning. This was done because the area was thus prepared for testing during normal daylight hours, and because the absence of wind led to more uniform sprinkling.

Cans were placed at each of the 28 grid points in each test area when sprinkling operations were in progress. The amount of water in each can was measured, and the arithmetic average of these measures was used to represent the rainfall for that application. Since the amount of water deposited along the boundaries of each area tended to vary (because of sprinkler patterns and drifting caused by wind), only the 14 grid points along the two long internal grid lines were used to compute this average. The variation in water depth at each grid point was recorded but is not available here.

The uniformity of the water distribution, as measured by the water collected in the cans, was qualitatively reported to be "reasonably good." Since the cans were not placed under pipe joints or sprinkler drains, they would not show moisture concentration due to leakage at these points. While a strenuous effort was made to reduce these leakage effects, as described above, they could not be totally eliminated.

Even absolutely uniform rainfall will result in concentrated areas of soil moisture, due to both the unavoidable contours and depressions of apparently level ground and variations in the soil itself. In a field test such as the one discussed here, it is not possible to determine the extent to which soft spots are caused by terrain and soil characteristics or by nonuniform distribution of water.

F. SOIL CHARACTERISTICS

The overall objective of this OUE was to evaluate the effects of rainfall on C-5A ground operations on unprepared airfield surfaces with strengths of CBR 9 and above.[13] The principal question is, given that ground operations are being conducted on dry soil with a rated strength of CBR 9, what is the effect of rain that wets the surface but does not reduce the CBR of the soil at substantial depths beneath the surface? This necessarily raises the issue of gradient of CBR with depth and the question of how this gradient shall be treated in determining the characterizing value of CBR for such soil (or, alternatively, in determining that the soil is too weak for the test to be run on it–i.e., CBR is less than 9).[14]

It was recognized that a thin layer of very soft and weak material above a thick layer of very hard and strong material would not pose a threat to adequate flotation of a vehicle traversing the area (though such a situation might result in skidding or in adhesion of the soft material to the vehicle).

In consideration of the foregoing, a "stop test" criterion was devised. If this criterion was not met, the soil was declared to be weaker than CBR 9, and the airplane would not be permitted to operate on it. The stop test criterion is as follows

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13. Reference 3, p. 3.

14. The appropriateness of CBR as a measure of operation of a wheeled vehicle on unpaved soil is discussed in Appendixes A and C.

Depth	CBR
0 to 6 inches	No restriction
6 to 12 inches	≥4
>12 inches	>9

This criterion was observed and, when it was satisfied, the "Resultant CBR" corresponding to a given test condition was calculated by averaging the CBR measured at 6-inch intervals from the surface to a depth of 18 inches.

Note that this second rule could yield a calculated value of resultant CBR less than 9, even though the first criterion is satisfied. For example, if the CBR values at 0, 6, 12, and 18 inches are 2, 4, 9, and 9, the calculated resultant CBR will be 6, even though the first criterion is satisfied. On the other hand, if the individual values of CBR are 2, 4, 9, and 25, the calculated resultant CBR will be 10.

If, however, the CBR values at 0, 6, 12, and 18 inches are determined to be 2, 3, 8, and 31, the stop test criterion will not permit operation, and the calculated resultant CBR will be 11.

The measurement of soil strength at the various depths and locations was accomplished by combining direct CBR measurements (made in pits adjacent to but separate from the specific test areas) with Airfield Penetrometer tests made in the test areas.[15] The unwetted soil was very hard, and its hardness exceeded the maximum reading of the penetrometer at all depths. Therefore the penetrometer was used only for measurements near the surface within the test areas after they had been wetted. Full-scale readings of the penetrometer usually occurred by the time a depth of 6 inches was reached. CBR values at 6-inch intervals, to a maximum depth of 18 inches, were then assumed to be equal to the values from the CBR pits at the same depths.

Three CBR pits were dug adjacent to the test areas before sprinkling began. The results from these tests are contained in Table 1.[16] Note that the variation about the mean at each depth is substantial. The column headed "average" was used to determine the CBR values at depths within the test areas at which the hardness exceeded the maximum scale of the penetrometer. In view of the variation with pit location shown in Table 1, and in view of the fact that the test areas were all in other locations, the use of CBR values from the "average" pit must be considered an approximation of uncertain accuracy.

Further, as discussed in Appendix C, the determination of CBR from penetrometer AI values is a procedure of questionable accuracy. For this test program, no direct measurements were made in wetted soil (penetrable by the Airfield Penetrometer) until the test program had been completed. When the tests had been completed, two CBR pits were dug in the extended test area and two more in the maximum area. Therefore, for the purposes of CBR determination during the tests and for the preliminary data contained in this report, the

15. For a discussion of CBR determination, both by direct measurement and from Airfield Penetrometer tests, see Appendix C, pp. C-4 through C-8.

16. The values given in Table 1 are preliminary, as are all other CBR and AI values. Final values of these quantities will be reported by the Waterways Experiment Station.

Table 1. CBR Values Measured at March AFB[a]

Depth (in.)	CBR				Range About Average
	Pit #1	Pit #2	Pit #3	Average	
Surface	17	21	30	23	+7 to -6
6	31	22	49	34	+15 to -12
12	25	33	32	30	+3 to -5
18	17	26	36	26	+10 to -9
24	15	16	22	18	+4 to -3
36	–	27	–	27	–

a. Values for each pit at each depth are an average of at least three independent measurements. Preliminary data are shown here. Pits were located adjacent to test areas. Measurements were made prior to water application to test areas.

assumption was made that the CBR value was equal to the AI determined by the penetrometer.

As shown in Figure 3,[17] the correlation of CBR with Airfield Index yields CBR less than AI for most (but not all) soils, particularly at low values of AI. Further, this appears to be more likely for cohesionless soils (sands) than for cohesive soils (clays). Preliminary results of correlations established from the pits in the wetted test areas after the tests were completed at March AFB are also shown in Figure 3, and these results indicate that for this low-cohesion soil CBR is less than AI. It can only be concluded that the conversion of the AI readings to CBR must be regarded with caution.

The resultant CBR values determined for the four different test areas (exploratory, normal, extended, and maximum) are given in Tables 2 through 5. For the areas in which water was applied progressively, the hardnesses are shown following each application of water. The AI values obtained at shallow depths for the watered soil are an average of values obtained at the two interior lines of grid points (14 points per area), the same points at which water depths were measured.

Table 2. CBR Values Considered To Be Effective In Exploratory Test Area[a]

	Depth (in.)	CBR[b]
One water application 1.75 inches	Surface	1.7
	6	3.3
	12	13
	18	26
	24	18
	Resultant CBR 12	

a. Preliminary data are shown here.

b. For CBR ≤ 15, CBR = AI.
For CBR > 15, CBR from average column of Table 1 is used.

As mentioned earlier, at the conclusion of the tests two CBR pits were dug in the extended area and two more in the maximum area. These pits permitted direct CBR measurements to be made at various depths in the wetted soil. The results from these measurements are shown in Table 6. Comparison of the average CBR results from this table with the corresponding entries in Tables

17. Taken from Reference 1, Figure 3.

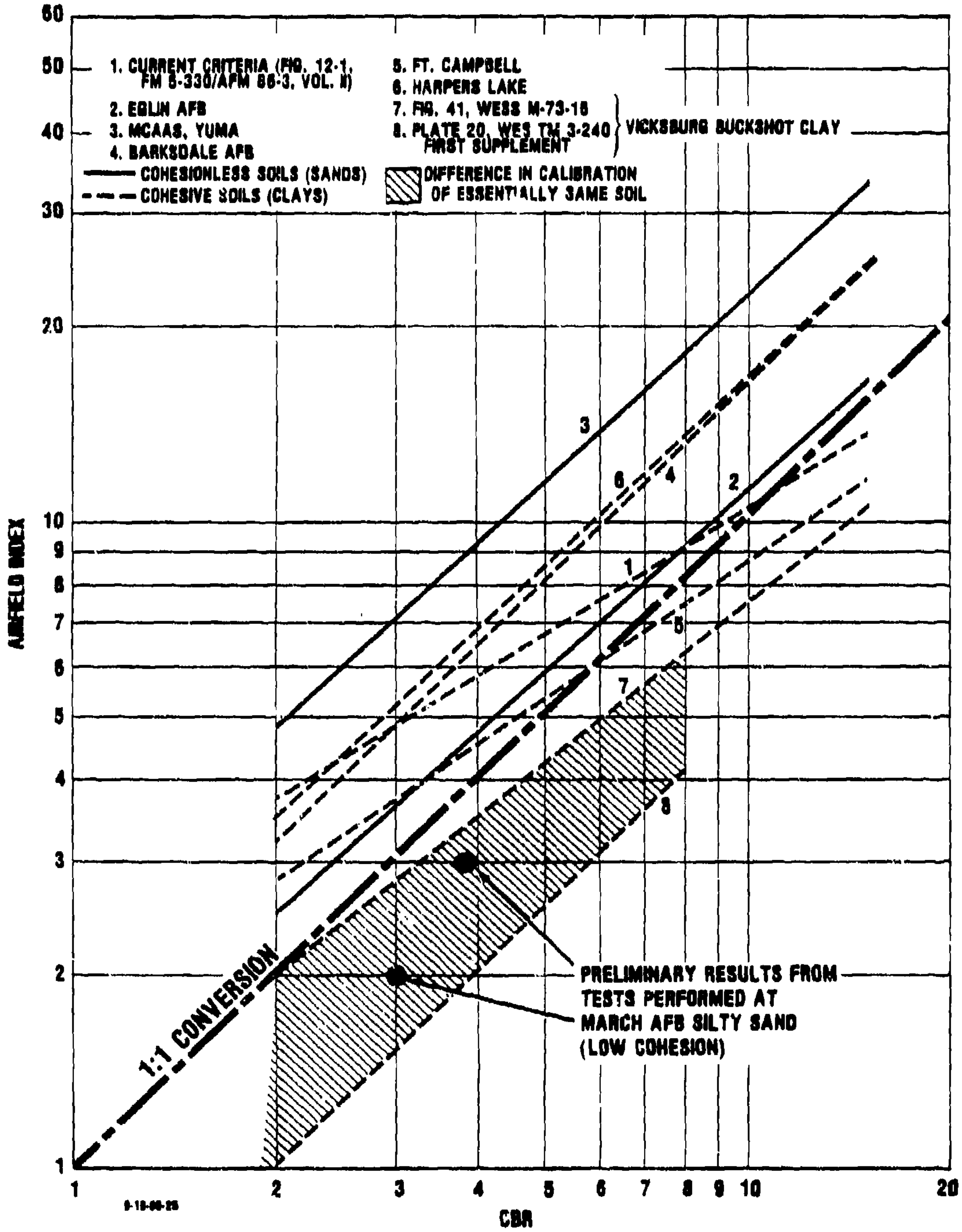

Figure 3. Comparison of Various Correlations of Airfield Index With CBR

Table 3. CBR Values Considered To Be Effective In Normal Test Area[a]

	Depth (in)	CBR[b]
First water application 0.52 inch	0-3	5
	3-6	15
	6	34
	12	30
	18	26
	Resultant CBR 22	
Second water application 1.27 inches (cumulative)	0-3	2
	3-6	7
	6	34
	12	30
	18	26
	Resultant CBR 20	
Third water application 1.75 inches (cumulative)	0-3	3
	3-6	7
	6-12	15
	12	30
	18	26
	Resultant CBR 16	

a. Preliminary data are given here.

b. For CBR ≤ 15, CBR = AI.
For CBR > 15, CBR from average column of Table 1 is used.

4 and 5 shows reasonable agreement, though there is considerable variation at the various depths.

Laboratory tests made at WES on soil samples taken from the test areas showed a Plasticity Index (PI) equal to 1. This indicates that the soil exhibited very low cohesive forces, and is consistent with its basically sandy character. It also means that this soil, unlike clay, exhibits little stickiness when wet. Results from the test are consistent with the laboratory findings, since wet soil thrown up onto the landing gear of the airplane showed little tendency to adhere and could be readily brushed away.

Earlier PI tests made on samples of soil collected by AFTEC at a slightly different March AFB location (obtained when March was selected to be the test location) showed a PI of 10, which is relatively high for silty soil. These tests were performed by a different laboratory. This difference again illustrates the variability of soil characteristics, the difficulty of replicating answers from soil tests, or the combined effects of both.

G. TEST RESULTS

The initial taxi tests (in the exploratory test area) and towing tests were performed at a weight of 425,000 pounds. All subsequent tests were performed at 665,000 pounds.[18] These weights are the minimum and maximum of those used during the earlier OUE tests reported by Reference 2. The center of gravity was at approximately mid-range for all of the tests.

The patterns proposed by the test plan [Ref. 3] for taxiing generally involved straight segments and turns of up to 270 degrees. Figure 4 shows the planned taxi patterns that were to be used in the normal test area.[19] These involved turns of varying magnitude, using several different amounts of nose wheel steering (NWS) angle. In the actual execution of the tests these patterns were not closely followed, but their basic elements were employed.

18. For discussion of the significance of these particular weights, see Reference 1, pp. 6 and 19.

19. See p. 3 for definition of normal test area.

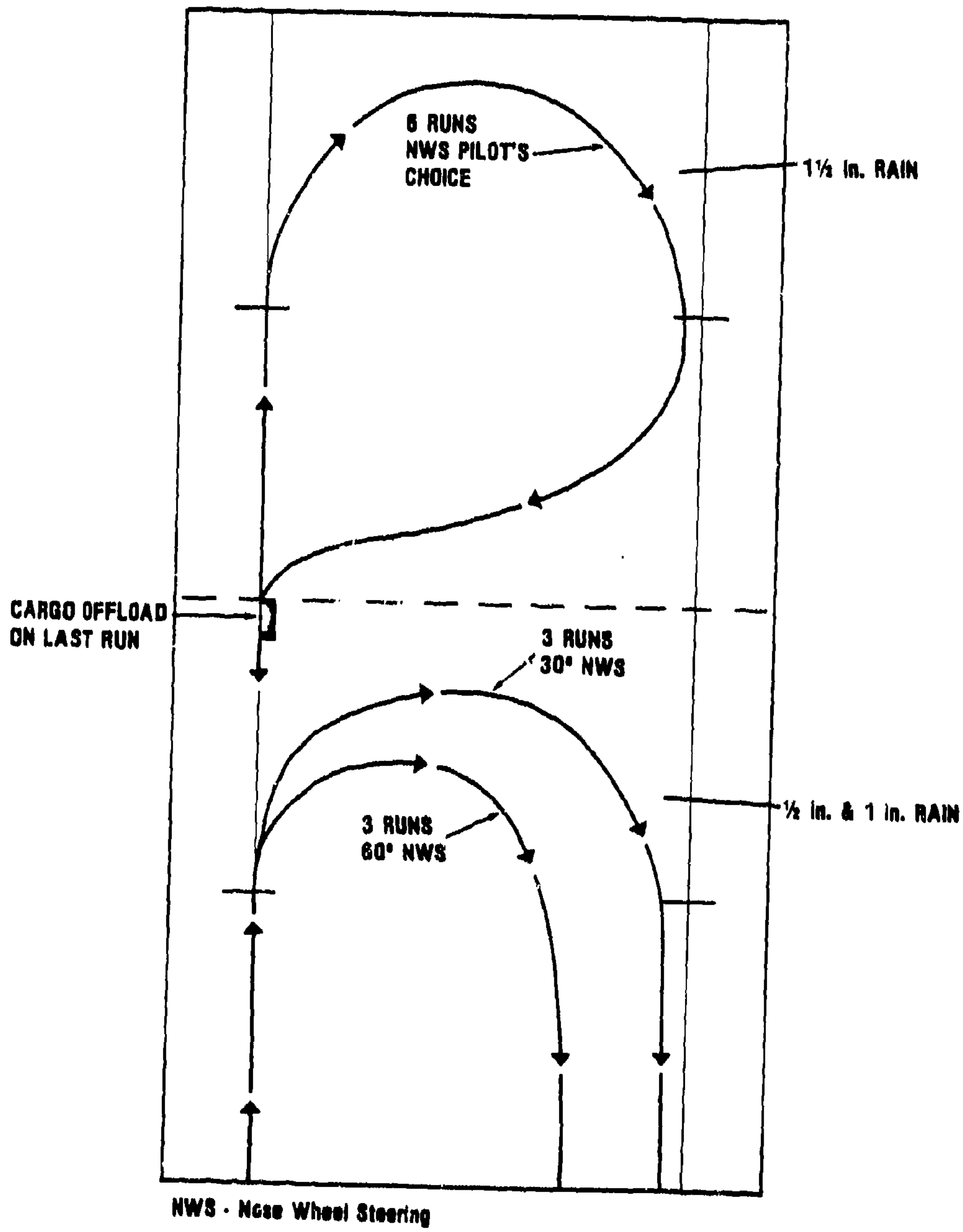

Figure 4. Diagram of Normal Test Area

Table 4. CBR Values Considered To Be Effective In Extended Test Area[a]

	Depth (in.)	CBR[b]
First water application 0.80 inch	0-3	3
	3-6	10
	6	34
	12	30
	18	26
	Resultant CBR 21	
Second water application 1.20 inches (cumulative)	0-3	3
	3-6	5
	6	34
	12	30
	18	26
	Resultant CBR 20	
Third water application 1.60 inches (cumulative)	0-3	3
	3-6	5
	6	34
	12	30
	18	26
	Resultant CBR 20	
Fourth water application 2.00 inches (cumulative)	0-3	3
	3-6	4
	6-12	10
	12	30
	18	26
	Resultant CBR 15	

a. Preliminary data are given here.
b. For CBR $\leq$ 15, CBR = AI.
For CBR > 15, CBR from average column of Table 1 is used.

1. **Tests in Exploratory Area**

The initial taxi tests were performed in the exploratory area. This area had received the first water application from the original sprinkler configuration.[20] Approximately 1.75 inches of water had been applied in a period of about 3 hours. However, the non-uniformity of the water distribution casts doubt on the validity of the measured value. The variation of soil strength with depth is given in Table 2, but this, too, is probably variable with location.

The test plan called for entering the area and then making a 180-degree turn to the right and exiting the area, followed by a repeat maneuver with a 180-degree turn to the left. The first turn was completed without difficulty, though substantial rutting and upheaval of the soil were observed. However, on the second turn, the inside rear main landing gear (MLG) truck dug deeply into the soft earth. The pilot relaxed NWS angle, and the nose wheels rolled straight for some distance (and coincidentally on relatively dry, hard ground on the edge of the wetted area). There was no skidding or scuffing of the nose wheel (as evidenced by the molded pattern of nose wheel grooves that were impressed in the soil). NWS angle was then again increased; the nose wheels entered a wet, soft area and were buried to approximately the diameter of the wheels. At this point the airplane was headed toward sprinkler system lines that were somewhat beyond the edge of the test area, and the pilot stopped with the nose gear buried as described, the inner MLG deeply rutted, and the outer MLG just emerging from the edge of the wetted area onto firm ground (approximately following the path that the nose gear had followed). The nose wheel was straightened without difficulty after the airplane had come to a stop.

20 For discussion of this sprinkler configuration, see p. 5.

The decision was made to move the sprinkler lines, restart the airplane straight ahead, and then turn in the opposite direction and exit over dry ground. This was accomplished without removing any soil from around the landing gear and without difficulty. Motion pictures of the nose wheel truck show it emerging through a large amount of soft soil, shedding this soil, and proceeding normally onto dry ground.

Table 5. CBR Values Considered To Be Effective in Maximum Test Area[a]

	Depth (in.)	CBR[b]
One water application 2.00 inches	0-6	3
	6-12	6
	12-18	15
	18	26
	Resultant CBR 13	

a. Preliminary data are used.
b. For CBR ≤ 15, CBR = AI.
For CBR >15, CBR from average column of Table 1 is used.

2. Tests in Normal Area

Following application of 0.52 inch of water (see Table 3), the airplane entered the area and made 180-degree turns—the first with 30 degrees of NWS, and the second with 60 degrees. The rutting was rather spotty, as if there were soft spots interspersed in a generally

Table 6. CBR Values Measured Directly In Extended and Maximum Areas at Conclusion of Tests[a]

[2 pits in each area]

	Depth (in.)	CBR	
Extended area (2.00 inches of water in 4 applications, with traffic after each application)	Surface	4	6
	6	4	3.5
	12	26	8
	18	30	28
	24	18	18
	Average	16	13
Maximum area (2.00 inches of water in 1 application, with traffic afterwards)	Surface	2.2	3.4
	6	5	2.6
	12	28	12
	18	17	24
	Average	13	10.5

a. Values for each pit at each depth are average of at least three independent measurements. Preliminary data are used.

hard area. At one point, on the first run with 30 degrees of NWS, the nose wheel plowed rather deeply; the left main gear then ran through the same area and left a localized hole about a foot deep (measured from the upheaved shoulders) and 10 feet long with steep entry and steep exit. The crew noticed nothing unusual about the motion of the airplane, and the airplane completed the entire run without difficulty. (At this time no one was aware of the effects of the concentrated moisture being produced by the sprinkler system, as described on page 7.)

The second run, with 60 degrees NWS, produced some spotty rutting, as had the previous run, but no concentrated soft areas were encountered.

Two more runs were then made with 30 degrees of NWS, and two more with 60 degrees—for a total of six runs in the area. The individual wheel tracks made during the initial runs were obliterated by multiple wheel passages; and, though the area appeared to be heavily trafficked, individual ruts were not particularly apparent.

A second application of water was then made to the area, bringing the total amount of water to 1.27 inches. The sequence of six taxi runs made in the previous test was repeated, but the pattern of turns was reversed. That is, the airplane entered the area on the opposite side and made turns to the left rather than to the right. Thus, while the wheel patterns crossed, they did not coincide. The results were similar to those observed after the first application of water. The soil condition after 6 runs appeared somewhat better than after 2, again because multiple passes obliterate individual ruts. It would be meaningless to attempt to define an individual rut depth in the test area, and, in any event, the distress of the surface did not increase with increased numbers of passes. No difficulties were encountered in making these runs.

A third, and final, application of water was then made, bringing the total amount to 1.75 inches (the three applications were made over an elapsed period of approximately 24 hours). After this watering it was discovered that concentrated drainage was causing localized soft spots that had grown to depths of as much as 3 feet. This problem has been discussed (on page 7) in the section on Simulation of Rainfall. It was decided that these frequent and deep soft holes, caused by peculiarities of the sprinkling system at that stage of its development, constituted a hazard and that additional taxi tests in the normal area should be cancelled. It is apparent that the one hole encountered by the airplane, following the first watering, was caused by the concentrated drainage from the sprinkling system.

3. Tests in Extended Area

The initial application of water to the extended area was 0.8 inch. The sprinkler system had been improved prior to this to substantially reduce the points of concentrated drainage that necessitated termination of tests in the normal area.[21]

The airplane was taxied in a manner similar to that used in the normal area following the initial watering, and with similar results. There was some minor rutting, but no major soft spots were encountered. The ground looked dry, but it was softened at the surface (see Table 4).

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21. See p. 7.

A second increment was applied 1 day later (total water was then 1.2 inches). When the airplane was taxied in the area, the results were similar to those of the previous day. During an offloading event, a fitting on a main hydraulic line (located in the wing root area) ruptured. This failure was not a consequence related to the special test or environment, and it occurs occasionally on C-5A aircraft during normal operations. The cargo doors were open and a ramp had been extended at the time the failure occurred, but the offloading of the cargo (vehicles) had not begun. The decision was to leave the vehicles aboard the airplane, which remained parked in the field overnight. The sinkage of the 665,000-pound airplane, at the end of the parking period, was about 4 inches. A replacement hydraulic fitting was obtained the next morning, and the repair was effected in the field without difficulty. It is interesting to note that a standard work stand (type B-2) was moved through the softened soil without particular difficulty and was rigged beside the airplane to give access to the wing root area.

On the same (third) day another increment of water was added to the extended area, bringing the total to 1.6 inches. The rutting produced by the airplane was not significantly deeper, and it appeared that compaction of the soil was occurring. In fact, after each application of water, the worst conditions were encountered in every case on the first or second passes. Compaction effects then appeared to take place, and, by the fifth or sixth pass, the situation improved. Note, however, that this might be a characteristic of the silty sand soil; the same results might not have been achieved on clay.

On the fourth day a final application of water brought the total to 2.0 inches. At this point, standing water was collecting in wheel tracks and depressions. The measured soil strength data (Table 4) indicated that the water was penetrating deeper. Rut depths of 6 to 8 inches were observed. On this day the airplane entered a deep soft spot that had developed near the south side (see Fig. 1) of the extended test area. The spot was approximately 50 feet wide and 150 feet long and had an AI value of about 2 down to a depth of about 2 feet. There was some indication that this spot resulted from concentration of water drainage caused by the local ground contour, but sprinkler system spillage may have been a contributing factor. The nose gear truck of the airplane passed through the area without difficulty, as did the right front main gear truck. The right rear main truck (which was operating in the "centered" mode since the airplane was proceeding straight at this point) settled into the area and plowed up a substantial ball of soil in front of it. Observers told the pilot to make a precautionary stop, though it is not clear that the airplane could not have continued through the area. The dirt was shoveled away from in front of the rear truck, and the airplane taxied out of the area without difficulty.

The airplane then re-entered the test area, avoiding the soft spot discussed above, and began a turn with 30 degrees of NWS. The pilot selected the rear MLG trucks to be free to caster during the turn (as is normal, but not mandatory, practice during a turn), and this appeared to cause an unusual action of the airplane. Before describing this action, however, a brief description of some features of the C-5A landing gear will help to explain what took place.

Figure 5 shows a footprint of the C-5A landing gear. The MLG is comprised of four six-wheel trucks. The nose-wheel assembly consists of four wheels and is steerable, by an irreversable actuator controlled by the pilot, through ±60 degrees. The two forward MLG trucks are fixed with respect to caster (steering) angle. The two rear MLG trucks can be locked in the uncastered position, or they may be freed to caster, at the pilot's selection, during turns. These trucks have a maximum caster angle of ±20 degrees, and they can be driven back to the centered position and locked by "power back" actuators, again selected by the pilot. The purpose of the castering is to permit the airplane to turn about a point that is located on an extension of the axle line of the forward MLG trucks with a minimum of wheel scuffing. The airplane can be turned with the rear MLG trucks locked in the centered position, but, on a

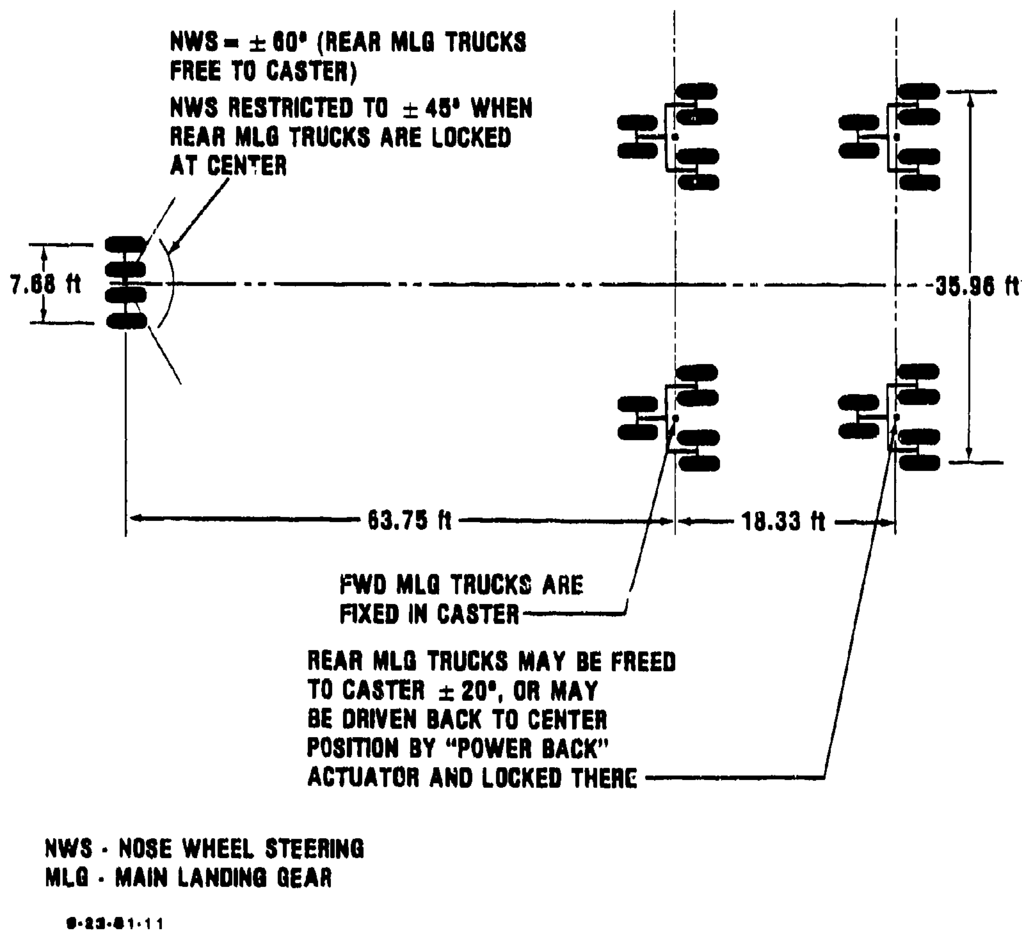

Figure 5. C-5A Landing Gear Geometry

dry paved surface, this increases the turning resistance of the airplane (and increases the loads in the landing gear members). In addition, current operating restrictions limit the NWS angle to a maximum value of ±45 degrees with the rear trucks locked.

With respect to the turn begun with 30 degrees of NWS in the extended area, the inside rear MLG truck castored until it reached its caster limit stop. (The kinematics of the landing gear causes the inner truck to caster farther than the outer truck during a turn, and there is evidence that, in soft soil, both trucks will caster farther at a given NWS angle than they will on hard soil or pavement.) At this point, this truck began to operate at a higher slip angle than the other three trucks, and its drag increased (an effect similar to that of applying the brakes on that truck). The airplane then pivoted around this truck, the truck digging rather deeply into the soil. The lightly loaded nose wheel was swept around at a substantial skid angle for a considerable distance, but with no adverse effects. The airplane was stopped, and the rear main trucks were centered by use of the "power back" actuators of the landing gear system. These actuators had no difficulty, with the airplane stopped, in rotating the trucks in the wet soil. The airplane then taxied out of the area without difficulty. It was judged unwise to attempt any further maneuvers in this area with the landing gear free to caster, since, with no load measuring instrumentation available on the airplane, it was not possible to determine the loads being imposed on the structure.

Following this, the airplane re-entered the test area and made a turn with 30 degrees of NWS, but with the main landing gear locked in the centered (uncastered) position. There was no excessive digging in or difficulty during the turn with this configuration. (In this configuration, all four MLG trucks would experience essentially equal slip angle or scrubbing. Though the total resistance is increased in a manner similar to braking on all four trucks, there is no tendency to pivot about a particular truck.) Thus there is some indication that the airplane might better be taxied on soft ground with the MLG locked in the centered position. It is again noted that current operating restrictions limit the airplane to a maximum NWS angle of 45 degrees when the MLG is not free to caster. Relaxation of this limit for operation on soft ground would require analysis, and probably tests as well, with an instrumented airplane.

This concluded the testing in the extended area.

4. Tests in Maximum Area

For tests in the maximum area, 2.0 inches of water were applied in a single watering that required approximately 20 hours to complete. The overall results of the soil strength tests that were made at the completion of the watering are shown in Table 5.

The maximum test area was obviously wet and soft at the start of these tests. It was decided to make the first taxi test a straight traverse through the area. The airplane made deep ruts immediately and dragged the bottoms of the landing gear trucks (rut depth greater than 8 inches). Its speed was slowed from entry speed, and the thrust was increased until two of the engines approached limit Turbine Inlet Temperature. It was apparent that the airplane was near the limit of its operating capability.

A second straight run was then made along the same general path that had been used for the first. This run was accomplished with noticeably less thrust—an estimated 10 percent less—than had been required for the first run.

A third run was made, with a further reduction of thrust. This again probably reflects a favorable result of compaction of the silty sand soil. Again, similar favorable results may not have occurred on clay.

A cargo offload was successfully performed on one of the latter passes.

A planned turn with 30 degrees NWS was abandoned, for this turn would have taken the airplane out of the compacted area and into fresh, soft soil. The pilot concluded that he did not have sufficient reserve thrust available for such an event, and the probability of becoming immobilized was too high to risk the attempt.

5. Effects of Dust and Mud

When the airplane taxied outside of the sprinkled test areas, the dry silty sand soil of March AFB pulverized into a very fine dust. The dust clouds so generated remained suspended in the air for long periods, and generally were transported considerable distances by the prevailing breezes before they diffused and disappeared. Though no adverse effects of this fine dust could be found on the airplane, there was evidence that the engines ingested some of it. It was found that dust entered the airplane through the air conditioning system, which draws air from the engine compressors, and the crew reported the occasional odor of burned grass in the cockpit, which must have originated from dried grass ingested by the engines.

Increased emphasis was placed on inspecting for adverse effects caused by the dust, but none was found.

Similarly, substantial amounts of soil were thrown onto the landing gear, but this did not adhere to the wheels and tires, nor to the structure of the landing gear or airplane. It was judged that this soil would not interfere with the functioning of the landing gear, and the soil was readily brushed from the gear. Note again that this particular soil exhibited little cohesion and that the same results might not have been obtained with clay.

6. Towing

Towing tests were conducted on a dry concrete ramp and from dry soil into the wetted exploratory test area on the first day of the tests. The auxiliary tow kit (which attaches to the main landing gear) and two adverse-terrain fork lift vehicles were used for towing. The links of the tow kit were equipped with strain gage instrumentation.

The tests on the concrete ramp were made to establish a base line towing force for comparison with the towing forces required on the unpaved soil. As would be expected from the C-5A towing tests conducted in the summer of 1980, this test was completed without incident.

Similarly, when the airplane and tow vehicles were positioned on dry soil, the towing was accomplished without difficulty. However, as soon as the adverse-terrain fork lifts entered the wetted area of the exploratory test area they spun their wheels, dug into the soil, and stopped immediately. No further towing tests were attempted.

7. Cargo Offload

Cargo offload was successfully accomplished without incident in both the extended and the maximum test areas. The hydraulic fitting failure that occurred (discussed above) during preparation for the cargo offload to be performed in the extended area was unrelated to the offloading event. The results of the offload tests were consistent with earlier offloads conducted on unprepared surfaces.

H. FINDINGS AND GENERAL OBSERVATIONS

The basic purpose of this OUE was to evaluate the effects of rainfall on the operation of the C-5A on unpaved surfaces with adequate strength for such operations prior to the rain.

A simulated rainfall was accomplished by the use of irrigation sprinklers. The experience gained in this effort showed that it is difficult to simulate natural rainfall over a substantial area and that localized anomalies, whose effects may be significant but difficult to evaluate quantitatively, are likely.

The soil at the test site was a silty sand. This soil exhibits low cohesion and produces neither the surface slipperiness nor the adhesion characteristics (sticking to the wheels and landing gear) that occur with a clay soil. However, it may be similar enough to sandy silt soils found in Central Europe, and at West German airfields in particular. Rutting, to approximately the depth of the softened (wetted) areas, did occur during inital taxi runs, but, on this silty sand soil, repeated passes tended to roll and reduce the rutting conditions.

The large gradient of soil strength with depth caused by the wetting of a rather shallow layer of soil makes difficult the determination of a useful and concise characterization of soil strength.

The airplane performed well under difficult circumstances, but it appeared to approach its performance (thrust) limitations under the maximum rainfall conditions simulated.

- Taxi patterns and turn radii generally made good appeared to be equivalent to those achievable on dry paved surfaces. There was no significant evidence of skidding on this soil.
- With the rear main landing gear trucks free to caster, the airplane tends to pivot about the inside rear truck during turns in which this truck reaches its caster stop. This causes the inside rear truck to dig in rather deeply and the nose wheels to skid sidewise. The installation of load measuring instrumentation would be necessary to determine whether excessive loadings are being generated when this occurs. The "caster back" actuators are able to return the rear trucks to the centered position in these circumstances, and the airplane can then move normally. Such an event occurred only when soil conditions were severe.
- If the rear MLG trucks are locked in the centered position, the airplane can turn without the digging and pivoting motion described above. However, current restrictions limit the amount of NWS that may be used in this configuration to 45

degrees. Analysis and additional testing would be required to determine whether this limit can be removed when the airplane is operating on soft soil.

- No maintenance problems peculiar to these tests or test environment were encountered. (A hydraulic line fitting failed, but this failure was not caused by the tests.)
- Cargo offloads were again performed without difficulty. There was no indication of difficulty due to uneven sinkage or settlement of the airplane, or from water or mud.
- Towing in the wetted test areas could not be performed because the tow vehicles could not generate sufficient tractive effort to move the airplane. The tow vehicles spun their wheels and dug into the softened surface.

These tests again illustrate the difficulty, and perhaps inappropriateness, of attempting to describe the strength of complex and variable soil structures by a single descriptor such as California Bearing Ratio. This measure was not devised to characterize the complex and dynamic action of a wheel rolling on soil, an observation succinctly illustrated by the following paradox.

- During these tests, the airplane approached its thrust limits when operating in the area of maximum rainfall and rutted the soil deeply. The CBR determined for these tests was 13.
- One year earlier, at Altus AFB after waiting nearly 2 weeks for the soil to harden sufficiently to rise to a rating of CBR 9, the airplane operated as easily as it would have on a paved surface and left barely detectable indentations in the soil.

REFERENCES

1. *C-5A Austere Airfield Operational Utility Evaluation, Phase I* (U), IDA Paper P-1546, December 1980, SECRET.

2. *C-5A Operational Utility Evaluation, Final Report (Phase I),* Air Force Test and Evaluation Center, Kirtland AFB, New Mexico, March 1981, UNCLASSIFIED.

3. *C-5A Operational Utility Evaluation Plan, Phase II (Project No. 80-019 2A),* Air Force Test and Evaluation Center, Kirtland AFB, New Mexico, May 1981, UNCLASSIFIED.

Appendix A

RESULTS FROM C-5A OUE CONDUCTED AT SHAW AFB, ALTUS AFB, AND EGLIN AFB

The following summary of the results of the C-5A OUE, conducted during July and August 1980, at Shaw, Altus, and Eglin Air Force Bases, is taken from Part 3, Chapter I, of IDA Paper P-1546, *C-5A Austere Airfield Operational Utility Evaluation—Phase I*, December 1980, SECRET.

J. CONCLUDING REMARKS

1. Bare-Soil Tests

(U) The C-5A OUE tests were generally satisfactorily completed on three different soils—clay/sand, lean clay,[1] and sand (with a grass-covered surface). These surfaces were not truly *unprepared* since they were parts of established airfields and, thus, had been graded. Compared with unprepared surfaces, they were smoother and less likely to contain significant obstacles. Similarly, all of the test sites were dry, so no tests were conducted on slippery surfaces.

(U) The test sites were given an overall CBR rating of 9 or more. However, CBR values in any naturally occurring soil are quite variable within the dimensions of the test sites, and there were locations (and depths) with CBR values less than 9.

(U) Substantial deep pulverization of the sand soil occurred and deep ruts (8 inches) were formed after a few traverses by the airplane (at all weights tested). Nevertheless, the airplane did not experience difficulty in moving or unloading on such terrain. Brake hydraulic lines were broken, but this could be prevented by a relatively simple rerouting of these lines. However, additional taxi tests with an airplane equipped with load-measuring instrumentation would be advisable before operation on sand surfaces was authorized.

(U) Towing on sand surfaces proved to be unreliable. The tow vehicles were not capable of consistently developing enough traction to move the airplane.

(U) The landing gear wheels and the engine exhaust blast caused dust clouds, but the dust did not interfere with operations. The engines did not ingest a significant amount of dust, nor was there a significant amount deposited on the working surfaces of the airframe. No maintenance problems caused by or peculiar to the environment were encountered.

(U) The ability to offload cargo was not impaired by operation of the airplane on the unprepared soil. The doors, ramps, and other equipment associated with the offloading operation performed without failure.

(U) Operation on AM-2 matting occurred without difficulty. However, there is a question about whether the soil beneath the matting was softened to the specified CBR value.

(U) A design requirement that the C-5A be capable of operating from surfaces whose strength is equivalent to unsurfaced clay with a CBR of 9 does not impose critical loads on the airplane itself. However, the design requirement does not refer to the capabilities of the C-5A. Rather, it states the airplane should not cause excessively rapid deterioration of the airfield surface and thus necessitate frequent surface maintenance efforts.

(U) In addition to its variability with position, it is questionable whether CBR is, by itself, an adequate descriptive index of wheel/soil interaction. It has been widely used for

1. (U) Preliminary analysis of the soil at Altus AFB classified it as lean clay. However, a more thorough, and later, soil analysis changed this classification to "sandy clay with a subgrade of silty clay." See p. 4. [Footnote added]

this purpose for many years. However, there are technical reasons that indicate that penetrometer data provide a better prediction of this interaction. In addition, the current practice of converting penetrometer observations to CBR values by using ad hoc penetrometer/CBR calibration relationships may well insert additional uncertainties caused by the vagaries inherent in establishing the penetrometer/CBR calibration.

(U) It is emphasized that CBR 9 soil is neither *soft* nor *spongy*. The lay observer, traversing it on foot, would only describe such soil as *hard*. In those parts of the world where temperate climates prevail, there will be substantial portions of the year when the CBR values will be considerably less than 9. Values of 3 to 5 may be rather common when the soil is moist to wet and the temperature is cool.

(U) The wheel/soil interaction is fundamentally different on coarse-gained (sand) soils than it is on fine-grained (clay) soils. There is theoretical evidence that the correlating parameters for these two types of soil are different, and there is experimental evidence that the values of the wheel performance parameters (e.g., tractive effort, rolling resistance, rutting) are also different for the two soils. A spectrum of performance parameters exists for soils with compositions between the extremes defined by sand and clay.

(U) If serious consideration is to be given to the operation on soil surfaces of such high-value machines as aircraft (and if the military success of such operations is to be relied on), then it is necessary that a better quantitative understanding of wheel/soil interaction and soil strength characteristics be established than presently exists. This is probably a rather long term undertaking. In the meantime, and lacking this fundamental understanding, the only reliable method for determining operating limits is substantial experience derived from an expanded test program conducted using a wide variety of soil types and climatic conditions.

Appendix B

RESULTS FROM C-5A OUE CONDUCTED AT GRIFFISS AFB

The following summary of the results of the C-5A OUE conducted in snow, during January 1981 at Griffiss Air Force Base, is taken from the Addendum to IDA Paper P-1546, *C-5A Austere Airfield Operational Utility Evaluation —Phase I*, December 1980, SECRET.

SUMMARY

(U) The C-5A OUE tests conducted at Griffiss AFB were observed from January 20-23, 1981.

(U) The airplane was taxied and unloaded in approximately 12 inches of dry snow without significant difficulty. The temperature during the testing varied from slightly above 0° to slightly below 32° F. The soil beneath the snow was hard. The pilots used techniques for taxiing the airplane that were somewhat different than would have been used on hard and dry surfaces, but these techniques were developed rapidly and were not difficult.

(U) The full range of weights used during the earlier (summer) tests was also used for the winter tests. No marked differences were observed as the weight was increased, and the usual modest increase of thrust required to taxi at higher weight was observed. Movement of the center of gravity forward noticeably (but not drastically) improved the effectiveness of nose-wheel steering.

(U) The airplane again operated without maintenance difficulties. However, brake lines and electrical conduits located beneath the main landing gear trucks were again bent and

broken by impact with snow and ice. This was similar to the problem encountered during earlier tests in sand at Eglin AFB, but the damage was less frequent. The problem can be solved by moving the brake lines and conduits.

(U) No difficulties were encountered with the airplane during cargo offloads in the snow. The critical elements of the offloading system appeared to be the vehicles used for materiel handling. None of the wheeled vehicles was capable of operating in the unbroken snow, although most could operate on snow traversed and compacted by the airplane. The tracked armored personnel carriers (APCs) operated on both unbroken and compacted snow. The time required for the offloading operation was approximately double that required during summer conditions, even though no difficulties were encountered.

(U) Wheel brakes were occasionally frozen by snow entering the brake mechanism and forming ice. It is necessary to sweep and clear the snow from the landing gear when operating in deep snow. In addition, the wheels froze to the surface when the airplane sat in the snow for sufficient time to perform a cargo offload. Additional thrust was required to break the airplane loose and begin taxiing. This caused no difficulty during the OUE, under the conditions that existed, but it is not known whether greater difficulties might be encountered under more adverse conditions.

(U) The amount of snow blown by the airplane varied but caused no problems. The loose surface snow was blown away rapidly during the initial taxi runs, resulting in a dense snow cloud behind the airplane. This cloud completely obscured the airplane from the sight of observers behind the airplane or on the outer side of its turn. However, the cloud settled rapidly, and, on subsequent runs, blowing of the settled snow (beneath the original loose surface) was much less.

(U) If the temperatures had risen above freezing, the snow would have become slushy and, thus, considerably more slippery. The results of the current test program do not provide information concerning what might occur under such conditions. Rather, further tests would be required to establish this information.

(U) An attempt was made by two tracked APC vehicles to tow the C-5A at its lightest weight. These vehicles towed the airplane completely successfully when both the airplane and the APCs were on the bare, paved taxiway. However, as soon as the APCs were placed on snow, they spun their tracks and were unable to move the C-5A. The APCs were judged to be best able—of the vehicles present—to tow the airplane, so no attempts were made with any other vehicles.

Appendix C

WHEEL/SOIL INTERACTION AND MEASUREMENT OF SOIL CHARACTERISTICS

The following sections on Wheel/Soil Interaction and Measurement of Soil Characteristics are taken from Part 3, Chapter I, of IDA Paper P-1546, *C-5A Austere Field Operational Utility Evaluation—Phase I*, December 1980, SECRET.

F. WHEEL/SOIL INTERACTION

(U) The soil covering the surface of the earth varies widely by soil type, by method of natural deposition, by later artificial treatment, and by climate. As would be expected, soil has been greatly studied by geologists and by civil engineers who attempt to determine its physical properties for structural (bases for foundations, etc.) and agricultural (tillage) purposes.

(U) Soil, of course, forms the foundation or subbase of paved roads. Therefore, a critical need exists for suitable measures or indexes of soil strength so overlying pavements can be designed to satisfactorily carry the predicted loads. Civil engineers have developed various methods of measuring subbase characteristics, and one of these, the California Bearing Ratio (CBR), has been widely used for the design of flexible pavements. The CBR measurement method was developed many years ago by the California Department of Highways and was adopted by the U.S. Army Corps of Engineers for designing flexible pavements for airfields.

(U) The successful design of a flexible runway requires, among other things, that the deflections of the underlying subbase be limited to small values and that no large penetration or upheavals occur. Thus, an important characteristic of the subbase is its ability to carry stresses with small deflections and no ruptures. This is a property akin to that described by the modulus of elasticity of elastic engineering materials (e.g., steel and aluminum). The CBR is such a measure; it determines a stress-strain relationship at a strain considerably lower than the rupture level.

(U) However, the critical problem caused by wheels rolling on a soil surface is rutting. Rutting is characterized by both rupture and substantial displacement of the soil. The rupture or failure of the soil generally occurs when its maximum allowable shear stress is exceeded.

(U) As noted above, the CBR test more closely resembles a test of modulus than it does a test of ultimate strength. Conversely, the penetrometer instrument causes rupture and its measurements are more influenced by ultimate strength than by modulus. (A penetrometer is a slender rod with a conical point that is thrust into the soil at a moderate rate. The force required to maintain this rate of penetration is observed at various depths below the surface.) Thus, it can be argued that the penetrometer reading is a better indicator of the critical wheel/soil interaction than is the CBR value.

(U) This possible basic difference between the meanings of CBR and penetrometer measurements (modulus versus ultimate strength) has been suggested by Freitag [Ref. 9]. This raises the question of whether the criterion of wheel/soil interaction is ease of maintenance of the unpaved area over an extended time (which would emphasize the deflection or modulus approach) or the determination of the worst conditions at which the airplane is capable of operation (which would emphasize the rutting or ultimate strength approach). The design requirements for the C-5A were directed toward the maintenance of the airfield surface, as discussed earlier, whereas the OUE was more concerned with the operational capability of the airplane.

(U) Only a limited amount of analytical and experimental work has tried to establish the relationships that determine the performance parameters of a pneumatic tire rolling on a soil surface. These performance parameters include the rolling resistance of a towed wheel (analogous to the wheels of an aircraft landing gear), the tractive effort and torque of a powered wheel (analogous to the driving wheels of a towing vehicle), and wheel sinkage (rutting). The relationships are derived in terms of both soil and wheel characteristics.

(U) The analytical work used dimensional analysis to derive correlating numbers. References 10 and 11 contain the results of this analysis and present experimental results from tests made with several different wheels operating on clay and on sand surfaces. The results appear to be very promising for the types of surfaces used.

(U) The performance parameters mentioned above are correlated with a Clay Number [Ref. 10] and a Sand Number [Ref. 11]. These numbers utilize two different soil characteristics measured by penetrometers. While the results are quite encouraging, they illustrate the first of many problems encountered with performance predictions for a wheel operating on a soil surface, especially as critical conditions are approached.

(U) The basic physical premises on which the analysis is based are, first, that the shear strength of the soil is exceeded, and, second, that the shear strength of the soil may be represented by the Coulomb equation that states:

$$\tau = c + p \tan \phi,$$

where

- τ is the ultimate shear stress of the soil.
- c is the shear stress capability due to the cohesive properties of the soil.
- p is the normal pressure exerted on the soil at the point of shear failure.
- ϕ is the internal friction angle of the soil (and $\tan \phi$ is basically the internal friction coefficient).

(U) The clay used for the experiments of Reference 10 was almost totally cohesive with negligible intergranular friction. For such a soil the penetrometer reading is independent of depth of penetration (if the hardness of the soil is constant, as it was for these tests). This penetrometer reading was used to develop the Clay Number.

(U) The sand used for the experiments of Reference 11 was almost totally frictional with negligible cohesive forces. For such a soil, the penetrometer reading increases linearly with depth of penetration (if the hardness of the sand is constant, as it was for these tests). This gradient value is the penetrometer value used to develop the Sand Number.

(U) Soil, as found in the field (even with uniform hardness, which is highly unlikely), usually has both cohesive and frictional characteristics. Presently, there is no analytical approach capable of dealing with this situation. In fact, although References 10 and 11 both show considerable success when dealing with rather idealized soil samples, the introductions to both of these references point out that "the prospects of early development of analytical equations to define the tire-soil interactions are not good."

(U) Perhaps an even more fundamental difficulty in quantifying wheel/soil interaction is the highly variable nature of soil properties with position, depth, and time. These properties can vary significantly within the dimensions of an airplane landing gear. Indeed, within one of the CBR test pits dug at Altus AFB, four CBR readings of 11, 5, 11, and 3 were taken along a line approximately 2 feet long. This kind of variation has caused Freitag to comment, in Reference 12, that:

> The problem with soil is that properties vary from place to place (over a wide range), and at a particular place, soil properties vary from day to day, depending on climate, weather and topography.

and

> It is found that results obtained in one study cannot be related to results obtained in another study at a different time or place.

(U) The potential value and problems of similitude testing were commented on in a paper [Ref. 13] presented at the Fourth Seminar on Similitude of Soil-Machine Systems at the University of Illinois in 1969. The following comments, from the introduction to Reference 13, summarize this potential.

> Scale-model tests based on similitude principles have played a major role in the development of aerodynamics and hydrodynamics. From this work has stemmed the capability to design and analyze systems involving fluid flows that are too complex for purely analytical techniques. Aerodynamics in particular has benefited from wind-tunnel studies based on similitude. The benefit has been not only in the immediate practical sense of providing detailed information about a particular component or a proposed design, but also, in a more fundamental way, in support of the evolution of a comprehensive aerodynamic theory. That similar accomplishments have not been forthcoming in soil-machine relations is due to at least two factors. One is simply that the level of interest and support, financially and technically, has been much less than in the aerodynamics field. The other is a technical one that arises from the broad variability of soils as compared to air. Whereas air has relatively well-defined and predictable physical characteristics, the characteristics of soil that relate to soil-machine problems are not well identified, may not be measurable, and certainly are not adequately predictable.

(U) Comparing soil-machine systems testing with similitude testing in aerodynamics and hydrodynamics appears to be quite pertinent. Certainly these latter disciplines have been advanced tremendously by similitude tests. It appears that soil testing may now be at the

position that wind tunnel testing was approximately 50 years ago. If the quantitative prediction of wheel/soil interaction is to be advanced to a level where its results can be accepted with reasonable confidence, additional emphasis must be applied to this area.

G. MEASUREMENT OF SOIL CHARACTERISTICS

(U) Numerous test procedures exist for determining soil characteristics, both in the laboratory and in the field. Most of these establish index quantities, such as CBR or penetrometer indexes, rather than measuring fundamental properties.

(U) The method for determining CBR and the test equipment used are described in Reference 14. Briefly, the field test consists of digging a pit to the desired depth and noting the force required to press a 3-sq. in. piston into the soil at a specified rate to a depth of 0.10 inch. The piston, force-measuring equipment, and drive mechanism are mounted on a truck that is fixed by jacks. The measured force is divided by the force required to obtain the same penetration in a reference material (crushed stone), and the quotient, expressed as a percentage, is the CBR value. A CBR of 10 means that one-tenth (10 percent) as much force is required to press the piston into the soil being tested as is required to press it to this same specified depth in the reference stone material.

(U) There are several penetrometers that the earlier description applies to. Of these, the one in general use consists of a long, slender shaft tipped with a 30-degree right circular cone and equipped with a simple dynamometer that permits direct measurement of the force required to thrust the penetrometer into the ground. Penetrometers with various shaft cross-sectional areas are used for soils of different hardness, but all of the penetrometers are geometrically similar. The penetrometer used for soils having the hardness common to airfields is called an airfield penetrometer, and it has a diameter of 0.50 inch (0.196-sq. in. cross-sectional area). This penetrometer, which was used for the C-5A OUE, is described in Reference 15. Its quantitative readings are referred to as the Airfield Index (AI).

(U) Penetrometer data can be obtained relatively quickly at numerous locations and depths beneath the surface. CBR data, on the other hand, are obtained much more slowly and require the digging of pits in the field if values at depths below the surface are needed. Therefore, it has become customary in field work, where CBR values are needed for a relatively large area and at a number of depths, to measure CBR directly at several scattered pits and then to obtain penetrometer readings at the same locations. A calibration curve is constructed to convert the penetrometer readings to CBR units, and this calibration curve is assumed to apply over the entire area of interest. Penetrometer readings are then taken at other locations within the area and are converted to CBR values from the calibration curve previously established. However, recall that it has been postulated that CBR and AI probably measure different properties of soil (the former measuring modulus and the latter measuring ultimate strength), and these different properties may not be connected by a unique relationship.

(U) At best the curve of CBR vs AI (the reading of the airfield penetrometer) varies considerably for various soil samples. This can be most simply illustrated by Figure 3, which is taken from Figure 34 of Reference 16. This figure shows the relationship between CBR and

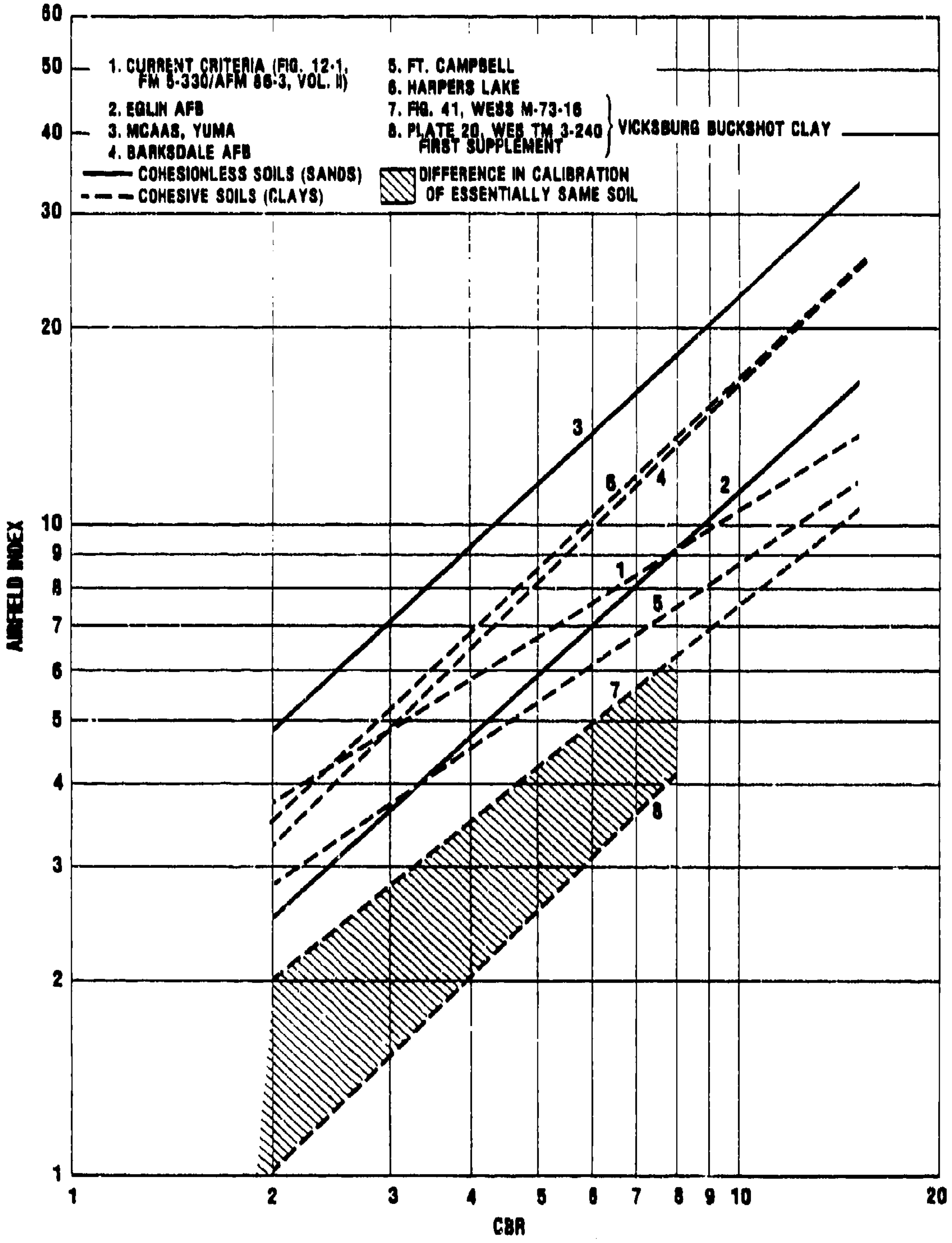

Figure 3 (U). Wide Discrepancy in Correlation of Airfield Index and CBR

AI for several soils. There is a wide variation of AI values at a given CBR. For example, the AI varies from 7 to 20 for a CBR of 9. Further, Curve 1 is generally given as the lower bound of CBR vs AI, and hence this curve is alleged to establish a conservative correlation between airfield penetrometer readings and CBR in the absence of a specific calibration curve. However, note that Curve 1 is in the midst of the curves for the various types of soils shown on Figure 3. In addition, Curve 8[5] is for the same type of soil from the same general location as Curve 7: both apply to Vicksburg Buckshot Clay (a highly plastic clay), but their values are from tests conducted at different times and reported in different reports. Curve 7 was established with field-measuring CBR equipment and Curve 8 with laboratory-measuring CBR equipment. There are differences of time and technique; however, note the large difference (shaded area) of overall result for, presumably, the same material.

(U) The actual calibration of CBR vs AI, as established during the OUE, is beset with vagaries. These vagaries result from the physical procedure used to establish the calibration curve, the scattered results, and the changes in the soil between the time that the calibrations were made and the time the tests were run (and the calibration applied).

(U) When the airfield penetrometer is used to determine AI measurements, it is thrust into the earth from the surface and is read at specified depths below the surfaces. However, when calibrated with respect to CBR measuring equipment, the penetrometer is thrust into the bottom of the pit (at whatever level that bottom then exists) and is read at specified depths below *that* level. This means that the CBR value at a given pit depth is being compared to penetrometer readings taken below that level.

(U) For example, Figure 4 shows a preliminary analysis of the data obtained at Altus AFB. The AI points were read 2, 4, and 6 inches below the level at which each CBR value was obtained. The solid lines on Figure 4 were faired by WES, and the dashed lines were generated by a least squares fit to the data points shown. The calibration curves so defined were used to convert AI values to CBR: the 2-inch depth curve was used when the penetrometer was 2 inches beneath the *natural surface*, the 4-inch curve when the penetrometer was 4 inches below the *natural surface*, and the 6-inch curve when the penetrometer was 6 inches *or more* below the *natural surface*. Furthermore, the penetrometer readings during the calibrations are taken at depths different from that at which the CBR values are measured as described in the previous paragraph so the calibration is confounded to an indeterminant degree by the gradient of soil strength variation with depth. This gradient is known to vary with location.

(U) The scatter of the data is apparent from Figure 4. In fact, the amount of scatter has been somewhat reduced by averaging three individual measurements of both the CBR and AI for each point plotted on Figure 4. This averaging tends to reduce random experimental error, and the substantial scatter that remains may result from the variability of the soil properties in the various locations at Altus AFB where the calibration tests were run. Similar results were obtained at the other test sites.

(U) A final uncertainty in the validity of the calibration data is caused by the lapse of time (and the accompanying change of soil strength) between the calibration tests and the

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5. (U) Curve 8 was added to the original set of seven curves on Figure 34 of Reference 16.

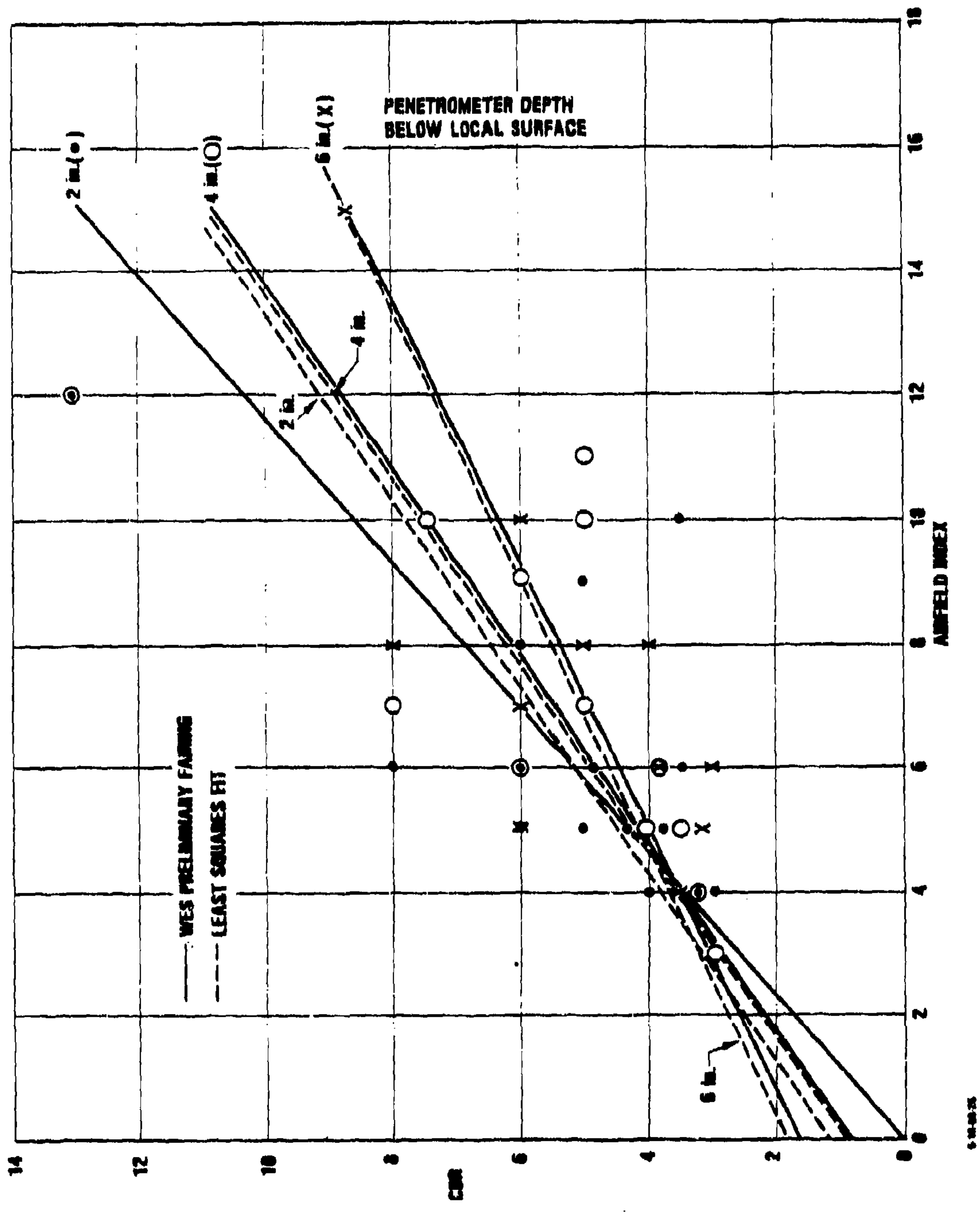

Figure 4 (U). Relationship Between CBR and Airfield Index at Alns AFB

actual tests with the C-5A. At Altus, in particular, the CBR data collected for the calibration revealed that the field was too soft for the tests. Very few calibration points exist on Figure 4 for a CBR greater than about 6. The tests were delayed for approximately 2 weeks to allow the test area to harden to CBR 9. However, the value of CBR 9 was determined from penetrometer tests converted to CBR value by linear extrapolation of the calibration curves.

(U) The uncertainties of the calibration procedure, coupled with the earlier discussion indicating that penetrometer data may be a more rational index of wheel/soil interaction, suggest that the direct use of penetrometer information may be preferable to attempting to utilize CBR data to determine the capability of an airplane operating on an unprepared soil surface.

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